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THE GENERATION AND RADIATION OF SUPERSONIC JET NOISE

VOLUME I
SUMMARY OF SUPERSONIC JET NOISE STUDIES

HARRY E. PLUMBLEE

PHILIP E. DOAK
CONSULTANT

The Lockheed-Georgia Company

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This volume is a summary report of the results of a 13-month research program on the generation and reduction of supersonic jet noise. This program was planned as the first phase of a four-phase effort. The specific tasks compromising this Phase 1 program, all of which have been carried out successfully, were as follows: (i) a thorough, critical review and evaluation of existing theoretical models for supersonic jet noise generation and radiation; (ii) development of the framework of a new, unified theory of aerodynamic noise; (iii) development of a new theoretical model of turbulent mixing region noise; (iv) development of a new theoretical model for calculating propagation and radiation of upstream noise; (v) a preliminary review of combustion noise; (vi) conduct of the most comprehensive set of tests to date on turbulent mixing region noise and shock-associated noise; (vii) a thorough review of the problems of jet flow measurement and analysis; (viii) development of new instrumentation for jet flow measurement (a crossed beam schlieren system, a laser doppler velocimeter and a pulsed laser interferometer); (ix) establishment of full facilities for the total program; (x) formulation of the program for future studies. Brief reports of results from all these tasks are presented in this volume (except for task (x) of which a full account constitutes Volume II of this six-volume series of reports.

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THE GENERATION AND RADIATION OF SUPERSONIC JET NOISE

VOLUME I

SUMMARY OF SUPERSONIC JET NOISE STUDIES

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FOREWORD

This series of reports, Volumes I-VI, was prepared by the Lockheed-Georgia Company, Marietta, Georgia for the Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio, under Contract F33615-71-C-1663. The span of the research was 1 May 1971 to 31 May 1972. The work described herein is part of the Air Force Aero Propulsion Laboratory's joint program with the Department of Transportation to define and control the noise emission of aircraft propulsion systems and was conducted under Project 3066, Task 306614.

Captain Paul Shahady, USAF, of the Air Force Aero Propulsion Laboratory (AFAPL/TBC) was the Project engineer.

Lockheed's Program Manager was Harry E. Plumblee and the Principal Investigator was Robert H. Burrin. The principals involved gratefully acknowledge the assistance of L. V. Mazzarella who operated the test facilities and data acquisition facilities; G. A. Wynne who helped in preparation of the jet noise reduction program; McCoy Matthews, R. B. Harrison and P. Aderhold who built and maintained the facilities; J. B. Allen who provided the preliminary design of the pulsed laser interferometer; R. Huie who helped in construction, operation and data analysis activities associated with the optics instruments; and D. E. Barrett who administered the submittal of all contractual data and helped in preparation of all the reports.

Gratitude is expressed to The University of Southampton for permitting Professor Philip E. Doak, Dr. Michael J. Fisher and Dr. Peter A. Lush; of the Institute of Sound and Vibration Research and Professor Geoffrey M. Lilley, head of the Aeronautics and Astronautics Department, and to The Georgia Institute of Technology for permitting Dr. Warren C. Strahle, to participate in the performance of the research reported in the six volumes of this report.

This report was submitted by the authors on 31 May 1972.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Ernest C. Simpson

ERNEST C. SIMPSON
Director
Turbine Engine Division
Air Force Aero Propulsion Laboratory

ABSTRACT

This volume is a summary report of the results of a 13-month research program on the generation and reduction of supersonic jet noise. This program was planned as the first phase of a four-phase effort. The specific tasks comprising this Phase I program, all of which have been carried out successfully, were as follows: (i) a thorough, critical review and evaluation of existing theoretical models for supersonic jet noise generation and radiation; (ii) development of the framework of a new, unified theory of aerodynamic noise; (iii) development of a new theoretical model of turbulent mixing region noise; (iv) development of a new theoretical model for calculating propagation and radiation of upstream noise; (v) a preliminary review of combustion noise; (vi) conduct of the most comprehensive set of tests to date on turbulent mixing region noise and shock-associated noise; (vii) a thorough review of the problems of jet flow measurement and analysis; (viii) development of new instrumentation for jet flow measurement (a crossed beam schlieren system, a laser Doppler interferometer and a pulsed laser interferometer); (ix) establishment of full facilities for the total program; (x) formulation of the program for future studies. Brief reports of results from all these tasks are presented in this volume (except for task (x) of which a full account constitutes Volume II of this six-volume series of reports).

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CHAPTER I

INTRODUCTION

The work reported in summary in this volume constitutes the first phase (Phase I) of a projected four-phase research program on the generation and reduction of the noise of supersonic jet engines. The end-objectives of the total projected program are as follows:

(i) to develop a unified theory whereby supersonic jet exhaust noise radiation, both near and far field, can be related to engine performance parameters and to the characteristics of the steady and unsteady flows both external and internal to the nozzle;

(ii) to provide specific guidelines for the design and development of effective and efficient supersonic jet noise suppressors;

(iii) to formulate a comprehensive technical plan for any additional research required on specific aspects of supersonic jet noise.

The work completed in Phase I of this program has consisted primarily, as specified in the technical task requirements of the contract, of the establishment and validation of the facilities and instrumentation and of the theoretical and experimental methodology and techniques that are necessary for the ultimate attainment of these end-objectives. In addition, however, over and above these task requirements, specific progress has been made in Phase I towards the attainment of these end-objectives, as follows:

(i) the conceptual and mathematical framework of a suitable unified theory has been explicitly established;

(ii) detailed theories (a) of jet mixing region noise and (b) of the propagation of noise in a supersonic jet flow, both external and internal to the nozzle, have been worked out explicitly and some preliminary numerical calculations have been performed;

(iii) an extensive set of measurements has been made of mixing region noise radiation and of shock-associated noise radiation from supersonic, and subsonic, jets and a detailed analysis of the results has been carried out, including full comparisons of these with predictions from existing theoretical formulas. (This set of measurements is believed to be the most comprehensive, self-consistent and reliable set of jet noise data obtained to date.)

In all, the report on Phase I of this research program consists of six volumes of which this, the first, is a concise and connected summary of the objectives, scope, programs of work, results and consequent conclusions of all the individual parts of the Phase I program. Also included are recommendations for future work arising from the work already completed.

Following on from this first volume, Volume II of the series is a statement of the proposed research program for Phases II - IV of the total program. Volumes III - VI contain the detailed, individual reports and discussions of work performed, and conclusions therefrom, on each of the individual tasks which taken together made up the total Phase I program.

The work has been carried out in the Advanced Flight Sciences Laboratory of the Lockheed-Georgia Company, during the period 1 May 1971 to 31 May 1972. In addition to Lockheed-Georgia staff, the research team has included, as active consultants, P. E. Doak (Institute of Sound and Vibration Research (ISVR)), M. J. Fisher (ISVR), G. M. Lilley (Department of Aeronautics and Astronautics) and P. A. Lush (ISVR), all from the University of Southampton, and W. C. Strahle, School of Aerospace Engineering, Georgia Institute of Technology. The granting to the consultant members of the team, by their respective institutions, of periods of leave of absence as required for the work is much appreciated. Also, Dr. Fisher and Professor Lilley have been concurrently members of the Jet Noise Panel of Rolls-Royce (1971) Limited and that company's agreement to their full participation in this research program is gratefully acknowledged.

CHAPTER II

OBJECTIVES AND SCOPE OF THE WORK

The required objectives of Phase I of the research program were clearly implied by the technical task requirements, which were as follows:

(i) to review and evaluate the various competing mathematical models used to date to explain the supersonic jet noise generation process, clearly stating the advantages and disadvantages of each model, this evaluation to include a discussion of any simplifying or limiting assumptions which affect the generality or applicability of the mathematical models and an assessment of the accuracies of these models based on available experimental data;

(ii) to conduct a preliminary investigation of the physical mechanisms of supersonic jet noise generation, assess their relative importance for the range of operating conditions typical of certain proposed supersonic jet engine systems, and formulate a comprehensive analytical/experimental program to investigate significant mechanisms in detail;

(iii) to formulate a detailed technical plan to investigate the interrelationship of nozzle performance parameters, local flow properties, turbulent structure, acoustic power production, and acoustic radiation, including the effect of upstream perturbations and instabilities caused by afterburning, rotating machinery, and primary combustion;

(iv) to conduct a detailed investigation of potential measurement and analysis problem areas; since advanced instrumentation techniques will be required to successfully accomplish the overall program, sufficient tests must be conducted to demonstrate the capability to accomplish the experimental portions of the follow-on phases.

Work along many of the lines indicated by the technical task requirements, and aimed at substantially the same objectives, was already in progress at the Lockheed-Georgia Company and/or the University of Southampton and Georgia Institute of Technology. In formulating the scope of work for the Phase I effort, therefore, it was decided to include in the scope of work not only all the required technical tasks (i) - (iv) as stated in the preceding paragraph but also as a major part of the effort, certain specific tasks which were envisaged in the contract statement of work as parts of later phases of the total program. These additional tasks were as follows:

(i) to extend the review and evaluation of existing, competing mathematical models to include the establishment of the conceptual and mathematical framework of a new, unified, exact theory of aerodynamic noise in general and of supersonic jet exhaust noise in particular;

(ii) to extend the preliminary investigation of the physical mechanisms of supersonic jet noise generation and the formulation of the technical plan for detailed investigation of the effects of the various flow and combustion parameters thereon to include (a) performance of the most comprehensive set of measurements to date of mixing region noise and shock-associated noise from supersonic jets together with detailed comparison of the experimental results with existing theoretical formulas, (b) development to working capability of a new theory of jet mixing region noise and (c) development to working capability of a new theoretical method for calculating the propagation of noise generated upstream inside the nozzle, or at the nozzle lip, out through the exhausting jet;

(iii) to extend the meaning of the phrase "detailed investigation of potential measurement and analysis problem areas" to include considerable development effort on certain new instrumentation: namely, the cross-beam schlieren, the laser-Doppler velocimeter and the pulsed laser interferometer.

Underlying this decision to extend the Phase I scope of work considerably beyond that which was strictly required were certain beliefs, or working hypotheses, generally accepted by the research team as a whole, deriving from the totality of the previous individual experiences and judgments of team members. In general, these working hypotheses have been confirmed and strengthened by the results of the Phase I work and thus continue to form the distinctive, basic, working philosophy of the team.

The first working hypothesis is as follows. Given that the total noise can be classified broadly into three components - mixing region noise, shock-associated noise and upstream noise - it is a generally valid first approximation to assume that these types of noise are linearly independent of one another. In other words, the total radiated noise intensity at a given observation point and in a given frequency band is the sum of the intensities of each of the component types and if, for example, the upstream noise and shock-associated noise mechanisms were not effective the mixing region noise intensity would remain the same as when they are effective. The results from the comprehensive set of supersonic jet noise measurements, described in Volume V, have provided further confirmatory evidence that in general this is indeed a valid working hypothesis, to a very good first approximation.

The second working hypothesis, following on from the first, is that, of the three broad components of the noise, the mixing region noise is of primary importance, not because it is necessarily the dominant component at all angles of observation and frequencies (which it is not) but because it always appears to be present and of significant level, especially in respect to the overall noise power output.

From these first two working hypotheses it follows that the essential first step towards achieving understanding of supersonic jet noise as a whole is to achieve an understanding of mixing region noise separately. This is also of some practical, as well as conceptual, importance because, for an ideally designed nozzle and ideal upstream flow conditions, neither upstream noise nor shock-associated noise would be present and the turbulent mixing region noise can thus be regarded as a kind of minimum noise output for a given nozzle (in the absence, of course, of additional, extraneous silencing devices). Experimentally, by careful design of the nozzle and the upstream flow supply system and plenum chamber, it is possible to reduce the upstream noise to negligible levels. If a given nozzle is then run at design conditions a jet flow free of shock cells will be obtained and hence the noise will be mixing region noise alone. Running the same nozzle at different, off-design pressure ratios will produce flows with shock cells and consequently with noise outputs that are comprised of a sum of the mixing region noise and the shock-associated noise components. Finally, known disturbances can be introduced upstream to give jet noise outputs comprised of all three components, including upstream noise.

The very comprehensive set of supersonic jet noise tests described in Volume V were planned on the basis of this philosophy, and, as has been mentioned, provided evidence generally confirming the validity of the philosophy. Consequently, and, of course, most important, the tests have provided clear, separate identification of mixing region noise and shock-associated noise, and also, to a limited extent, of some possible types of upstream noise.

The third working hypothesis was that by development of Lilley's new theory to working capability, it should be possible to accurately predict mixing region noise, both near field and far field, for both subsonic and supersonic jets, hot and cold. Comparisons of these predictions with the experimental results, in detail, should then lead to the required basic understanding of mixing region noise. In the Phase I work, good progress has been made in bringing the new theory to this working capability and preliminary numerical results obtained from the theory are very promising in their indication of trends that have also been observed in the experimental results (Volume IV). Full development of the theory and detailed comparisons with the experimental results are planned, with a very high priority, for Phase II of the total program.

The fourth working hypothesis was that none of the many possible mechanisms for generating noise in a supersonic jet could be accurately and unambiguously identified and defined, nor could possible interdependences between mechanisms be properly considered, until a complete, unified theory of aerodynamic noise generation could be constructed, in which also propagation effects must be clearly and unambiguously defined and distinguished from source effects. It was implied by this working hypothesis that the "acoustic analogy" formalisms of Lighthill, and others, whatever their merits in terms of initial mathematical simplicity, did not constitute satisfactory theories in this context. Again, the validity of this working hypothesis was generally confirmed by the work performed in the Phase I effort. The critical review and evaluation of existing theoretical models (Volume III) provided ample evidence, of a very fundamental nature, of the limitations of Lighthill's acoustic analogy formalism and of other previous theories. Also, as had been hoped, it was found to be possible to construct, from Doak's previous "identification" scheme, the full conceptual and mathematical framework of a suitable, unambiguous unified theory (Volume III).

The fifth working hypothesis was that, notwithstanding the possibilities that ultimately some single, easily measurable scalar quantity completely specifying the acoustic source strength distribution might be found, such quantities as "near field" pressure or density fluctuations were definitely not suitable for this purpose, in general, and there was hence no alternative for the foreseeable future but to pursue, with the utmost vigor, the task of developing instrumentation capable of measuring all the primary field quantities in jet flows (e.g., the three velocity, or linear momentum, components, pressure and entropy). Because of the recent rapid advances in instrumentation science, especially in respect to laser and other optical instrumentation, it was also possible to hope for some success should an instrumentation development program be undertaken as part of the Phase I effort. These hopes, too, were generally fulfilled by the results of the Phase I work. A crossed-beam schlieren system of full capability has been developed, solution of only a few (and soluble) problems remains before a laser-Doppler velocimeter (for fluctuating velocities) can be similarly brought to full capability and also results of considerable promise have been obtained in the development of a double-pulsed laser interferometer (Volume VI).

Thus it was found possible in the Phase I effort to carry out the program implied by the enlarged conception of the scope of work, including not only the required technical tasks (i) - (iv) but also the additional tasks (i) - (iii), with a considerable degree of success.

CHAPTER III

RESEARCH PROGRAM AND RESULTS

III.1 INTRODUCTION

The main, broad headings under which the work performed in Phase I, and that planned for later phases, can be classified are as follows: unified theory, turbulent mixing region noise, shock-associated noise, upstream noise and instrumentation development. Because of the natural division of labor among the team members, however, and because many of the tasks inevitably provided information about more than one of these main classification subjects, it is more convenient to report the work that has been carried out under volume headings that do not completely coincide with the main headings. The volumes in which the work is reported in detail are as follows:

Volume III:	Progress toward a Unified Theory of Jet Engine Noise;
Volume IV:	Theory of Turbulence Generated Jet Noise, Noise Radiation from Upstream Sources and Combustion Noise;
Volume V:	An Experimental Investigation of Jet Noise Variation with Velocity and Temperature (including Appendix A: Turbulence Mixing Region Noise Data and Appendix B: Shock-Associated Noise Data);
Volume VI:	Jet Flow Measurement and Analysis with Special Emphasis on Remote Sensing Devices: Crossed Beam Schlieren, Laser-Doppler Velocimeter, Pulsed Laser Interferometer.

From these volume titles, the volumes in which material on any one of the main headings may be found is fairly evident. The distribution of the principal contributions to the main subject headings among the volumes can also be shown as follows:

unified theory - Volume III;
turbulent mixing region noise - Volumes IV and V;
shock-associated noise - Volumes V and IV;
upstream noise - Volumes IV and V
instrumentation development - Volume VI.

In Section III.2 of this chapter a very brief outline of the Phase I technical program plan is given. The remaining sections of the chapter, III.3, III.4, III.5 and III.6, are, respectively, summary reports of the work described in detail in the corresponding volumes III-VI.

III.2 PHASE I TECHNICAL PLAN

The Phase I Technical Plan was comprised of the following specific technical tasks (the volume locations of the reports on these tasks are also indicated):

(i) to perform a thorough, critical review and evaluation of existing theoretical models for supersonic jet noise generation and radiation (Volume III);

(ii) to develop the conceptual and mathematical framework of a new, unified theory of aerodynamic noise in general, and supersonic jet noise in particular (Volume III);

(iii) to develop Lilley's new theory of turbulent mixing region noise to working capability (Volume IV);

(iv) to develop, to working capability, a theoretical model for calculating the propagation of upstream noise out through the exhausting jet and into the far field (Volume IV);

(v) to conduct a preliminary review of combustion noise (Volume IV);

(vi) to conduct the most comprehensive set of tests to date on the turbulent mixing region noise and the shock-associated noise of supersonic jets, with emphasis on the noise dependence on jet velocity and jet temperature (Volume V);

(vii) to thoroughly review the problems of jet flow measurement and analysis with special emphasis on remote sensing devices (Volume VI);

(viii) to develop new instrumentation for jet flow fluctuation measurements, in particular a crossed beam schlieren system, a laser-Doppler velocimeter and a pulsed laser interferometer (Volume VI);

(ix) to develop and validate the experimental facilities necessary for the experimental work planned for Phase I and envisaged for the later phases (II-IV) of the total program (Volume V and Volume VI);

(x) to formulate a program for future studies (Phases II-IV) of supersonic jet noise generation and reduction (Volume II).

III.3 VOLUME III: SUMMARY REPORT

III.3.1 Critical Review and Evaluation of Existing Theoretical Models for Supersonic Jet Noise Generation and Radiation

The urgent present need for a unified theory of aerodynamic noise has been justified (i) in terms of engineering requirements and (ii) as a logical scientific development in view of progress made in the subject in the last two decades.

A thorough critical examination of the conceptual adequacy and physical scope of previously existing theories of aerodynamic noise has revealed a number of new aspects of many of the theories. Restatement and generalization of the original work by Stokes, Kirchoff and Rayleigh on coupled linear acoustic-vortical-thermal fluctuations has provided both important insights on the physical interrelationships among these modes of motion and a straightforward approach to the formulation of the theories of Phillips and Lilley for aerodynamic sound generation and propagation. The approach also directly provides the Pridmore-Brown equation describing propagation of sound in a unidirectional transversely sheared mean flow.

From this generalized Rayleigh approach, definite conclusions emerge as to how acoustic, vortical (turbulent) and thermal types of motion can be unambiguously identified and observed in the simplest linearized situations.

When Lighthill's acoustic analogy theory, and other acoustic analogy theories such as that of Ribner, are then examined, the conclusions reached from the generalized Rayleigh approach make it obvious that Lighthill's use of mass density as the "acoustic" variable, rather than pressure, is physically tenable only in the limit of vanishing viscosity and thermal conductivity (i.e., zero Stokes number).

Construction of solutions of the acoustic analogy equation describing aerodynamic noise generation and propagation, for situations in which the source distribution occupies a finite volume in space, has been carried out to provide illustrations of how the fluctuating pressure (or acoustic mass density) inside the source distribution is related to that outside. Examination of these solutions has shown that all three of Lighthill's published criticisms of Ribner's "isotropic source tensor" theory are unjustified, the reason being that Lighthill's objections were based on the behavior of acoustic fields near, but outside, point multipole sources, rather than on the true physical situation of source distributions of finite extent. The new solutions obtained also show that if source distribution elements are sufficiently compact and sparsely distributed in the source region, then the strength of Ribner's "isotropic source tensor" can indeed be closely related locally to the fluctuating pressure (or acoustic mass density) within the correlation volumes of these source elements, as was originally supposed by Ribner.

It has been shown, however, that simple acoustic analogy theories, such as those of Lighthill and Ribner, are basically unsatisfactory physically, regardless of how convenient they may be mathematically. The reason for this is basically that these theories are too synthetic. As the new solutions for the acoustic field inside the source distribution have shown, these theories essentially simply relate the pressure fluctuations (or mass density fluctuations) inside the source distribution to those outside, without giving any explicit information as to the ultimate causes of the fluctuations or as to the reasons why any particular relationship between the pressures inside and outside the source distributions should occur. This conclusion is not at all surprising in view of the fact that the prototype of the acoustic analogy theories, Lighthill's theory, was specifically designed to deliberately avoid all questions of the interdependencies among acoustic, turbulent and thermal types of motion, and also of refraction, convection, scattering, and radiation impedence influences on the sound produced by the mean flow gradients, the mean temperature gradients and the turbulence itself. These questions were all deliberately avoided on the grounds that (twenty years ago) they were too complicated and difficult.

In the light of present engineering needs, and present theoretical and experimental capabilities, however, not only are these explicit questions no longer too complicated and difficult but also they are precisely the phenomena that can be controlled by engineering design, so that detailed knowledge of them is required in order that designs can be evolved that take advantage of whatever possibilities exist for reducing and controlling noise through these phenomena.

Theories in which such effects are explicitly considered include those of Crow, Doak and Lilley. Doak's result for a linearized situation has been shown to include that of Crow as a special case - namely that of small mean Mach number. Doak's result validates the form of the inhomogeneous equation obtained by Crow and extends this validation to situations of arbitrary mean Mach number in which, however, mean velocity gradients are relatively small. The final conclusion from the critical review is that if a unified theory is to be developed, a good starting point would be Doak's identification procedure taken together with Lilley's mixing region noise theory.

III.3.2 Formulation of a Unified Theory of Aerodynamic Noise Generation and Propagation

On the basis of Doak's identification procedure a unified theory for aerodynamic noise generation and propagation, suitable in particular for applications to supersonic jet engine noise problems has been constructed, and the essentials of this theory have been described in Chapter III of Volume III. This theory has been shown to contain Lilley's mixing region noise theory as a special case. There are no restrictions inherent in the theory on either the magnitudes or directions of mean momentum and temperature gradients. The basic definitions required for full generality

of application of the theory to arbitrary fluid flows have been given. Quite generally, the theory provides a framework for studying all the interdependencies among the acoustic, thermal and turbulent components of the fluctuating motion, respectively, and these components have been unambiguously defined.

Finally, four specific problems have been defined. An intensive program of study of these problems can be expected to lead, in the first instance, to establishment of the new generalized theory in sufficient detail to provide accurate quantitative predictions of all types of supersonic jet engine noise, within a unified framework. These types of noise, specifically including mixing region noise, "shock-cell" and other "potential core" noise (i.e., all types of "shock-associated" noise), "upstream noise", including exit-plane noise, and noise generated upstream of the tail pipe exit by combustion, turbine blading, etc. The theory also appears to be of a form from which ultimately, after the quantitative prediction methods have been established and validated by comparisons with experimental results, parameter studies and other methods for engineering design purposes can be evolved.

III.4 VOLUME IV: SUMMARY REPORT

II' Generation of Sound in a Mixing Region

Lighthill's theory of aerodynamic noise, formulated nearly 20 years ago, had provided the main foundation for work on jet noise in general and mixing region noise in particular. Brilliantly conceived, and delightfully simple in its derivation, it has nevertheless proved to be a major stumbling block in attempts to dovetail the characteristics of the fluid flow with the sound field generated by it except in an elementary sort of way. The basic difficulty of the whole problem is that only a minute fraction of the available kinetic energy in the flow is radiated as noise and any crude approximation to the disturbed properties of the flow would inevitably lead to gross errors in estimating the noise generated.

Lighthill's theory has predicted many of the overall characteristics of the noise from jets such as the eighth jet velocity power for the noise intensity of jets operating at subsonic Mach numbers, and together with the modification introduced by Ffowcs Williams has predicted the jet velocity cubed law for the noise intensity of jets operating at high supersonic Mach numbers. However, the directivity pattern of the sound generated has been, at best, only predicted with fair accuracy in some cases, where convective amplification is present, and has been unsuccessful in its prediction when effects such as refraction have existed.

To attempt to fill these gaps in aerodynamic noise theory is fraught with danger since most inevitably one has to give up an exact formulation of the problem to one which is essentially approximate. The challenge is, however, one associated with finding a source function in terms of flow quantities that are either known or can be derived or even measured,

and which are not basically changed as a result of the presence of the radiation and its interference with the flow, and with the interference of the radiation on the flow. It is believed that such a formulation has been found in the present work. Basically it is not new and in fact was originally derived by its present advocate (Lilley) many years ago in seeking a formulation of the related problem of turbulent wall pressure fluctuations in supersonic flow. This work followed, in turn, from a revamping of Lighthill's formulation by Phillips. It certainly seems that Phillips was the first author to seek a better understanding of the jet flow and of its inter-relationship with the noise radiated by it. In the present work this same path has been followed, of concentrating on the flow and its interaction with the radiation.

The basic differences between this new approach and that of Lighthill have been explicitly described and the subtleties in the comparative differences in the final results for the intensity of the radiated sound have been explained. However, in the time available, it has not been possible to complete a detailed numerical evaluation and estimation of jet noise characteristics over a wide range of jet parameters. Some of the preliminary results are, however, new results and will greatly change many of the well established concepts of jet noise generation and source location. In addition, some of these results are already helping to throw light on some of the yet unexplained characteristics of the generated noise as found from the experimental program. (see Volume IV for details.)

The next stage of the work is clear. The whole analysis must be converted, for computational purposes, to handle the case of an axi-symmetric jet; at present only the outer solution, covering the radiation field, is formulated for a circular jet. The second task is to find improved values of the eigenvalues and eigenfunctions for the dominant pressure modes in the flow field. Some ideas on how to derive these for a wide range of practical jet paremeters have been formulated which should lead to an estimation of the dominant noise source constituents.

The experimental program, dovetailed with the current theoretical program, will greatly assist in this breaking down of the complexity of the structure of the turbulent mixing region and in elucidating those characteristics of it which dominate the noise generation. As formulated at present the theoretical model of the source function is known to be crude. It is hoped that during the course of the work it will be built on and refined. Without a back-up experimental program concentrating on the fluid mechanics of the turbulent mixing region of the jet this will not be possible.

It is finally believed that until the structure of the jet mixing region is known in sufficient detail, and thus is fully understood, the chances of developing noise suppression schemes would appear to have little chance of anything but partial success. Equally firmly, it is believed

that the development envisaged of this program on mixing region noise has excellent chances of leading rapidly to the establishment of guide lines for noise suppression schemes and targets for the noise suppression.

III.4.2 Noise Radiated from Sources Upstream of the Nozzle Exit Plane

For many years the controversy and indecision in connection with the subject of jet engine exhaust noise due to upstream sources has been a major embarrassment. Significant amounts of such noise appear to be present (at least in the belief of many observers) in many situations of interest including both full-scale engine noise situations and laboratory model jet noise situations. In the case of laboratory jets it is well known that such noise can occur and that in many cases, if extreme care is not taken over the upstream flow and acoustic conditions to silence the upstream sources, it can certainly dominate the total radiated jet noise.

Perhaps the major obstacle in the path leading to an adequate understanding of upstream noise has been the fact that previously available theoretical analysis has been completely unable to cope with the problem of indicating the location of a particular "upstream" noise source, given the acoustic radiation field associated with it. The reason for this is that an upstream flow disturbance may cause noise in at least two ways. First, it may constitute a noise source inside the nozzle, creating acoustic disturbances there which then radiate out of the nozzle and through the jet as acoustic disturbances. Second, the upstream flow disturbance (a turbulent eddy, say) may be convected out through the nozzle and then interact with, say, the nozzle exit lip, or jet shock cells, or the jet mixing region, to constitute a noise source (or sources) in these neighborhoods. It is clear that the differences in propagation conditions inside the nozzle and/or through the jet for the different possible acoustic disturbances under consideration are important as distinguishing characteristics in deciding whether the noise comes from one of the possible source positions or another. Also, in the absence of knowledge of the effects of these propagation conditions it is only too easy in interpreting results to think that radiated noise variations with flow parameters, say, are due to variations in the source strength when they could equally be due to variations in the propagation conditions.

As a natural extension of theoretical work previously in progress at the Lockheed-Georgia Company and ISVR, University of Southampton, it has been possible in these Phase I studies to develop a theoretical method to a working capability, suitable for numerical computations, for calculating the propagation through the jet and out into the radiation field of any acoustic disturbance prescribed over the jet exit plane.

The basic equations used in the theoretical model are the full mass, momentum and energy transport equations of an ideal, compressible, inviscid and non-heat-conducting fluid, linearized with respect to the fluctuations only. The basic geometry is spherical, the jet exit "plane" being a circular segment of the surface of a sphere of appropriate radius, out of which a jet is issuing of prescribed, realistic mean flow and mean temperature characteristics. For applications to jet noise problems this "appropriate" initial sphere turns out to have a radius reasonably large compared with acoustic wavelengths of interest. This permits use of some approximate, but highly accurate, functions describing the radial dependence of the propagation, which had been obtained in some previous work. With the basic equations expressed in spherical coordinates, it is possible to make use of these functions, after the azimuthal dependence has been eliminated by the method of separation of variables, to eliminate the mass density and particle velocity fluctuations from the equations and thus obtain a partial differential equation for the pressure alone, as a function of radius and polar angle. Because of the use of the approximate radial functions, as mentioned previously, this equation can finally be reduced to an ordinary differential equation (with polar angle the independent variable) for the pressure, having coefficients that are functions of radius and polar angle (expressing the dependence of the mean flow and temperature on these variables), which is valid over a certain finite radial interval. Strictly speaking, therefore, one obtains a set of such equations, each valid in one of a sequence of concentric spherical-shell-type regions. In the absence of mean flow and mean temperature gradients, all these equations reduce directly to the familiar ordinary second-order differential equation for the associated Legendre polynomials.

The boundary conditions (representing realistic situations) for this sequence of differential equations are fairly easy to establish. For example, a radiation condition may be appropriate as the radius goes to infinity, and either acoustic "hard-wall" or "soft-wall" conditions may be specified over the surface of the initial sphere not occupied by the jet orifice. Over the jet orifice itself the distribution of fluctuating pressure, or particle velocity, may be specified. At the interface between neighboring shells, the usual conditions of continuity of pressure, and/or of fluctuating particle displacement, as appropriate, apply.

In the absence of specification of conditions on the initial sphere, the set of equations may be regarded as constituting an eigenvalue/eigenfunction problem and solved numerically for the analogs (as distorted by the specified mean flow and temperature conditions) of the associated Legendre polynomials. Then, when conditions on the initial sphere are given, these conditions can be expressed in terms of an appropriate sum of these "distorted associated Legendre polynomials" for the first spherical shell (in a manner exactly analogous to that used with the associated Legendre polynomials in the standard acoustic problem of radiation from a non-uniform piston set in a sphere), the solution finally

being carried out through the concentric shell regions into the radiation field.

Numerical programs for these solutions have been established and validated, for cold jets. The straightforward extension of these to include hot jets is planned for early completion in the continuation program.

III.4.3 Combustion Generated Noise

Although not financially connected with the Lockheed study a parallel study of combustion generated noise has been taking place at the Georgia Institute of Technology. The work completed to date has reasonably set forth the unknowns in combustion noise and has given guidance for continuing work to determine the importance of combustion noise in afterburning turbojets.

Virtually all of the present body of experimental results comes from turbulent free jet premixed or diffusion flames in laboratory size scales (< 1 in). No data exist on flames held by bluff body stabilizers. Theoretical work has been able to isolate the origin of the noise, but the scaling rules indicated depend too heavily upon the turbulence structure to attempt a scaling of laboratory results to engine hardware. Consequently, experimental results are required in hardware simulating actual turbo-propulsion system combustors.

Primary efforts required in this area are a determination of the scaling rules for the turbulence structure in bluff body stabilized flames, data acquisition on noise power radiated from bluff body flames and a determination of the effects of enclosures upon the noise generation process. Sufficient theory exists at the present time to scale results if the above efforts yield meaningful data.

III.5 Volume V: SUMMARY REPORT

III.5.1 Facilities and Instrumentation for Jet Noise Measurements

The jet noise measurements were performed in the anechoic chamber at the Lockheed-Georgia Company Aerospace Sciences Laboratory. This has an 11 feet by 11 feet by 17 feet free field volume. The interior is completely lined with anechoic wedges, made from glass fiber inside sheets of "hardware cloth" (wire mesh for rigidity), which provide a 99 percent echo-free environment above a frequency of 100 Hertz. The chamber is completely vibration isolated from surrounding structure being mounted on large coil springs. It has an ambient sound pressure level below 20 dB. A spring-tensioned cable floor, suspended from the walls, provides for easy access to the interior of the chamber. The room was designed for testing of model jets.

One of the primary objectives of the program was to investigate turbulent mixing region noise in a shock-free supersonic jet flow. Therefore, nozzles were designed to obtain supersonic flows which would have the closest possible similarity to subsonic jets. Each jet flow was to have uniform velocity across the nozzle exit plane, be free of shocks and have a jet boundary which would deviate from a circular cylinder only because of shear layer growth. Five different nozzles were chosen for the experimental program. The base nozzle was a convergent nozzle with a 2-inch diameter exit. For the fully expanded supersonic flow tests, four convergent-divergent nozzles, each with a 2-inch diameter exit, were chosen for operation at nominal Mach numbers of 1.2, 1.4, 1.7 and 2.0. The design and manufacture of the convergent nozzle is a relatively simple matter but the convergent-divergent nozzles are particularly difficult in both design and construction. The contour of the divergent section downstream of the throat must be very carefully controlled in order to expand the flow smoothly to the exit plane. The design and manufacture of these nozzles was therefore carried out with the utmost care. Accurate calibrations of the completed nozzles were carried out, to ensure that the design requirements had been met (the M=1.2 nozzle proved to be only partially satisfactory, the other three being fully satisfactory).

The control of mean flow parameters is probably the most critical aspect of a jet noise test since the mean flow pressure and temperature directly control jet velocity. Errors in mean pressure are reflected in radiated sound pressure to approximately the fourth power. The main air supply continuously delivers 20 pounds per second of clean, dry air at 300 psi. In addition, storage tanks retain 12,000 pounds of air at 300 psi for higher demands. The main air supply is initially controlled with a 4-inch automatic regulating pressure control valve, which is located within the acoustic laboratory. This main control valve isolates the noise tests from pressure demand fluctuations in other facilities to some extent. Either temperature or pressure is used as the control function. Downstream of this valve cold air is delivered to the Marquard Corporation Sudden Expansion (SUE) Burner, through a 2-inch automatic-regulating control valve. This valve is the primary controller on pressure within the burner system. In order to control both pressure and temperature to a high degree of accuracy for jet noise tests, hot and cold air are mixed upstream of the main plenum, located beneath the anechoic chamber. The cold air valve is automatically regulated by the plenum pressure while the hot air valve is controlled by plenum temperature. In addition, a 1-inch automatically regulated control valve is installed in parallel for fine control on the pressure and for the very low flow velocities. These servo controls provide ideal regulation of test pressure and temperature simultaneously. A 2-inch manually controlled valve is installed in the cold air line to supply cooling air direct to the anechoic room. This air passes through a muffler on the outside wall and enters below the cable floor of the room.

In order to eliminate the possibility of any extra noise originating through the nozzle, such as valve noise, etc., a special muffler and

settling chamber was constructed and installed immediately upstream of the nozzle.

The microphones used for the jet noise measurements were positioned on an arc of radius 6 feet, corresponding to 36 nozzle diameters. They were mounted on a frame of wire mesh to minimize reflections. The frame was attached to the room wedges and stabilized laterally by thin steel wires across the room. The arc of microphones was located in the plane of a room diagonal in order to be as far from the jet exit plane as possible, without being too close to the room wedges. Twelve one-quarter inch microphones were arranged at 7½ degree intervals, from 15 degrees to the downstream jet axis to 97½ degrees. In order to determine the effects of noise radiated in the upstream direction, particularly in the shock - associated noise tests, another frame of wire mesh was mounted beneath the cable floor with facility for mounting a further seven microphones at 7½ degree intervals from 105 degrees to 150 degrees, for alternative use with the twelve microphone frame.

Conventional electronics were used to record the sound pressure during the noise tests. A twelve channel ¼ inch B & K microphone system was used, incorporating a twelve channel B & K Model P-220 microphone power supply unit, and twelve model 4136 microphones. The responses from the twelve microphones were recorded on an Ampex Model FR-1300 FM-Direct 14 channel tape recorder. An Ampex Time Code Generator and Search Controller were used for input to channel 14 to expedite the location of data on tape for subsequent analysis.

The noise data was analyzed using a Hewlett-Packard Model 8804-A real time 1/3 Octave Audio Sprectrum Analyzer. Noise data was recorded on the tape at 30 inches per second, but in order to obtain the 1/3 octave spectrum up to 40 KHz the tape speed was reduced to 7½ ips on playback. This yielded a 1/3 octave spectrum from 200 Hz to 40 kHz. The spectral data was displayed using two different techniques. During the actual spectral analysis an x-y plot of the spectrum was obtained. Also the 1/3 octave levels were recorded on digital magnetic tape using a Hewlett-Packard Model 2547A Digital Computer connected to a Kennedy Model 1406 Incremental Tape Recorder for later detailed analysis using a data reduction program developed for use on the Univac 418 digital computer (see Appendix A of Volume V). The program lists the 1/3 octave band levels for each microphone and calculates the spectrum level and the overall level. In addition the program calculates difference spectra for comparison with theory.

III.5.2. The Jet Noise Experiments

The purpose of these experiments was to accurately measure the noise fields of representative supersonic jets, to compare the results with predictions from existing theoretical formulas and to determine some features of the variation of the noise with mean jet velocity and mean jet temperature. It was necessary first to measure the turbulent mixing

region noise, in order to define by direct observation the basic noise field that is always present for both subsonic and supersonic jets. It was arranged that other types of noise, such as shock-associated noise and upstream noise would also be present in at least some of the tests and these were studied separately.

It was believed, on the evidence of previous extensive experimental results on subsonic jets, obtained at the ISVR, University of Southampton, and on the basis of some theoretical arguments, that at low frequencies the observed turbulent mixing region noise of both the subsonic and supersonic jets tested would be in agreement with prediction formulas derived from Lighthill's "acoustic analogy" model in which the noise is regarded as generated by a certain, equivalent source distribution of acoustic quadrupoles. For the same reasons, it was believed that at higher frequencies, where refraction of the sound by the mean shear layer becomes important, this model would not be adequate. In order that comparisons of the experimental results at low frequencies with these theoretical predictions could be satisfactorily made, it was necessary to measure the sound field in great detail, so that any discrepancies between theory and experiment would be clearly and unequivocally evident. Thus it was necessary to measure noise spectra for wide ranges of angular positions and jet velocities, and at closely spaced intervals in these ranges. It was also known that in order to measure jet mixing region noise at low velocities (below about 1000 ft/s), it would be necessary to remove all upstream noise from valves and pipe systems. This was achieved by using a muffler and a large contraction ratio between the plenum chamber and the nozzle.

Heating of the air flow was used to maintain the exit static temperature at a constant value independent of the jet velocity. In this way it was expected that the effects of temperature could be separated from the effects of velocity. For supersonic flows it was necessary to have suitable, carefully designed, convergent-divergent nozzles to ensure a shock-free expansion of the flow.

In order to measure the shock-associated noise it was necessary to fix the boundary conditions for the sound field near the nozzle. It was known that the discrete component of shock-associated noise depends upon a feedback loop in which the sound field interacts with the nozzle lip. To standardize the boundaries, the nozzle was lagged with sound absorbing material to provide a free field environment, or a hard baffle was placed in the exit plane of the nozzle to reflect the sound. The shock-associated noise was measured for both under-and over-expanded nozzles.

A preliminary experiment to investigate upstream noise sources was carried out by reducing the contraction ratio of the nozzle from 36:1 to 4:1. This would increase the upstream flow velocity by a factor of 9 and would presumably generate more boundary layer noise. Unfortunately, this experiment was not completely successful because of instrumentation problems which escaped notice at the time the results were taken.

All the other experiments were carried out quite successfully with the exception of a few of the supersonic jet tests at the hottest temperatures. The desired conditions were unobtainable because of a temperature limitation on the muffler and plenum structure and because at these high mass flows the anechoic room temperature could not be fully stabilized.

Notwithstanding the several difficulties and limitations encountered, this set of subsonic and supersonic jet noise tests is confidently believed to have provided what is by far the most comprehensive and reliable set of data available to date. A complete listing of this data is provided in Appendices A and B of Volume V.

III.5.3 Turbulent Mixing Region Noise: Results and Discussion

Gratifyingly, the results of the measurements of turbulent mixing region noise displayed, in general, the main trends that had been expected in respect to frequency spectra, distribution in angle, jet velocity, and, with one striking exception, jet temperature. This exceptional result may be regarded as the principal "new" (i.e., unexpected) information obtained from the tests, and, as such, it will be described first.

For the heated jets, at Mach numbers above $U_j/a_o = 1.0$, there was an unexpected reduction in the sound intensity at 90° to the jet axis. On theoretical grounds, it can be argued that this sound intensity should vary as $\rho_m^2 U_j^8$, where ρ_m is approximately $\sqrt{\rho_j \rho_o}$. For the case when $T_j/T_o=1.0$, the intensity should vary only with the velocity factor. It was found, however, that the observed intensity fell below the U_j^8 line by about 5 dB at most frequencies and by some 10 dB at high frequencies ($fD/U_j=3.0$). This was in contrast to the cold results, in which the stagnation temperature rather than the static temperature was constant. In this case the intensity varied more or less as U_j^8 and the density correction appeared to be unnecessary, although, of course, it was very small. It does not appear that the difference between the two sets of results can be explained on the basis of a density correction alone. At most this would account for a difference of about 5 dB at high frequencies and 2.5 dB at intermediate frequencies. It is possible that the appearance of some kind of shock-associated noise could also be contributing to the difference between the cold and hot cases. It has been observed that this shock noise may not disappear entirely at full expansion, and it is Mach number rather than velocity dependent. The intensities in the two cases at the same Mach number are rather similar. This result needs further investigation by extending the temperature and velocity range to cover this region with good overlap: say, $T_j/T_o > 1.0$ and $U_j/a_o > 1.0$. In addition it will be necessary to carry out some heated tests at constant stagnation temperature to see if these agree with the cold tests.

In addition to these unexpected results at the highest temperatures, there were only two other areas where the results were not quite as expected, both these other exceptions being of minor significance. First, at the lower velocities the expected variation of sound intensity with temperature or density did not appear to occur, but perhaps this is not surprising as the temperature corrections are small and probably less than the experimental scatter. Also it was found that the experimental arrangements were not fully satisfactory for jet noise measurements below U_j/a_o=0.5 approximately. In this region the measured jet noise levels are between 70 and 80 dB, in a 1/3-octave band. The reason why measurements were not accurate below these levels is thought to be due to the lack of sensitivity of the Brüel and Kjaer 1/4-inch microphones which were used. The manufacturer's handbook quotes a minimum sound level of 70 dB overall for these. This situation could be easily remedied, of course, by use of ½ inch microphones.

The directivity of the jet mixing region noise was compared in detail with the formulas based on Lighthill's theoretical model. As expected, the agreement was found to be generally good provided the frequency was less than about 0.15 a_o/D for the downstream arc and less than about 0.30 a_o/D for the upstream arc. Above these frequencies, the observed directivity changes its form significantly from that predicted by the Lighthill formulas and it appears that refraction is indeed important. Thus the directivity in the downstream arc shows a behavior clearly reminiscent of the cone of silence which would be predicted by ray acoustics. The critical frequency and directivity for the downstream arc are in agreement with those found in previous work by Lush.

It had been expected that a very accurate picture of the discrepancies between Lighthill's model and the measurements could be obtained by suitably processing the data. The method consisted of taking each set of measurements at a given jet velocity and temperature and comparing the spectrum at a given angle with that at 90° to the jet axis. The variations with velocity and temperature, respectively, at 90° were investigated separately. Specifically, the method consisted of taking the observed 90° spectrum and calculating from it, by theory, what it should be (theoretically) at any other angle. Essentially, the theoretical prediction amounted to shifting the 90° spectrum in frequency by the Doppler factor calculated on the assumption that the sources were moving at the eddy convection speed, and then raising the level of the spectrum according to the Lighthill model convective amplification factor. The difference between the predicted and measured spectra would then give a measure of the discrepancies between the theoretical model predictions and the experimental results.

It was expected that at low frequencies good agreement would be obtained and that it would be possible to obtain conclusive information on the possible existence of a preferred orientation of quadrupoles. Unfortunately the low frequency information was satisfactory only above about 200 Hz and the range of 200 Hz to 1000 Hz was not sufficient to obtain

an overlap when the Doppler shifts were applied. In this region, also, the measurements were affected by instrument noise and lack of sensitivity. Below 200 Hz the microphones were coming into the near field of the sources especially at angles close to the axis.

Because of these difficulties it was not possible to evaluate the theory at low frequencies as carefully as is desirable. There was some evidence that the modified Doppler factor was not predicting the measurements correctly at supersonic eddy convection speeds. It was not possible to investigate this accurately; similarly it was not possible to confirm or refute the existence of a $\cos^4\Theta$ type quadrupole orientation.

It was also hoped that the critical frequencies at which refraction begins could have been accurately determined as a function of angle, jet velocity and temperature. This also was not fully possible because of the same difficulties, although some comparisons were made which suggested that the effect of temperature on refraction is very small except possibly at low jet velocities.

These particular limitations of the present set of measurements can be rectified relatively easily, simply by repeating the relevant measurements, with greater microphone distances (about 10 ft, say) being used to lower the limiting frequency to about 100 Hz, and with more sensitive microphones (e.g., Brüel and Kjaer ½-inch).

In conclusion, as various, and mostly relatively minor, limitations of the measurements have been described in some detail in the preceding paragraphs, it is necessary to reiterate the main, positive achievements of the tests. The test data constitutes very comprehensive evidence that for both subsonic and supersonic jet turbulent mixing region noise, hot and cold, the Lighthill-Ffowcs Williams formulas do not correctly predict the spectral shapes and/or directivity for the subjectively important medium and high frequency ranges. The formula predictions are reasonably satisfactory only for the lower frequencies. There are clear indications from the experimental results that the refractive effects neglected in the derivation of the Lighthill-Ffowcs Williams formulas play an essential role in determining the medium and high frequency spectral shapes and directivity. The very comprehensive set of data obtained remains available for comparison, in due course, with predictions from Lilley's new theory of mixing region noise, from which comparison it is believed a complete and correct understanding of turbulent mixing region noise can be obtained.

III.5.4 Shock-Associated Noise: Results and Discussion

The shock-associated noise measurements have been analyzed sufficiently to confirm the existence of two types of shock noise, one being a "periodic" (perhaps almost periodic), or "discrete", component consisting of a fundamental frequency and its harmonics and the other being a fairly broadband component but with a well defined peak frequency.

The results show that these two components have essentially the sam source.

In the case of the discrete component the sources are phased together by a feedback of sound to the nozzle lip. For this reason it was essential to standardize the boundary conditions at the nozzle. Two extremes have been tested since real conditions can be expected to lie somewhere between these two extremes. In one case the nozzle and plenum chamber exteriors were lagged with sound absorbing material to provide a free field environment and in the other case a hard baffle was placed in the exit plane of the nozzle to reflect the sound field, thus providing images of the sources.

An explanation of the discrete phenomenon was originally given by Powell and the present results generally confirm his theoretical model for calculating the fundamental frequency and the directivity of the radiation. However, the character of the individual sources is not included in Powell's model. The theoretical directivity is entirely due to phase differences among the various sources, and any inherent directivity of the sources would be superimposed on that obtained from the Powell model. By controlling both plenum pressure and temperature it is possible to vary the jet Mach number independently of the jet velocity. For the discrete radiation these phase differences depend upon emission angle and jet velocity. Thus it is possible to maintain the phase differences at constant values while varying the Mach number. If the phase differences are constants any variation observed will be the variation of the individual sources.

This technique has been used with some success in these experiments. When the jet velocity is held constant, the fundamental and first overtone both vary in a similar manner with Mach number, whereas this is not the case when velocity and Mach number vary together.

It appears that the intensities of the discrete components vary as a high power, near six, of the parameter $\sqrt{M^2-1}$. It may be shown that the square of this parameter is proportional to the pressure difference across a normal shock and thus it seems likely that this is a useful parameter for describing the source strength of shock-eddy interactions.

The discrete radiation has harmonics of the fundamental because the waveform is not sinusoidal but tends toward an N-wave. The harmonics, however, show different directional characteristics.

Some time after Powell put forward his model for the discrete component, it was realized that the broadband radiation is essentially from the same sources but without the feedback. Although the radiation is not now discrete it has a well-defined peak frequency, which again is accurately predicted by the theory derived from the Powell model.

It is possible, also, to modify Powell's original model to describe the broadband radiation in more detail. In this case, the spectral density of the radiation is derived as a function of the source spectral density and some weighting factor involving the phasing of the sources. Again it is possible to keep this phasing factor constant and examine the true variation of the individual sources. In this case it is not necessary to operate at constant jet velocity; the phasing will be constant if the frequency is chosen such that the factor, (f_s/V_c) $(1-M_c \cos\theta)$ is kept constant (e.g., the peak frequency). However, experiments at constant jet velocity do show that the broadband levels vary primarily as a high power, near six, of the same parameter used previously: i.e., $\sqrt{M^2-1}$. When the Mach number is held constant it appears that there is little variation of the level with jet velocity.

The presence of a reflecting baffle did not alter the broadband radiation at all, but it did have some effect on the discrete component. The levels of the tones were generally increased by about 10 dB, which is more than the 6 dB that would be expected on a simple doubling (by reflection) of the number of sources. It is presumed that the doubling of the pressure amplitude at the nozzle lip somehow leads to extra extraction of energy from the flow. There is a small change in the discrete frequency which is as yet unexplained.

It was found that heating the flow did not significantly affect either the discrete or the broadband components, although there were some changes in the discrete frequencies which could possibly be explained on the basis of an increased ambient speed of sound.

Over-and under-expanded supersonic flows radiated essentially the same shock noise, the frequencies and levels still depending on the fully expanded Mach number. At the point of full expansion both tones and broadband noise decreased very appreciably in level, but the broadband component did not entirely disappear, showing that even at full expansion some shock-turbulence interaction may occur. This of course means that meaningful measurements of supersonic jet mixing region noise must be made with special care, in the full realization that some contamination by this broadband "shock-associated" noise may still be present, even in a fully expanded jet.

III.6 VOLUME VI: SUMMARY REPORT

III.6.1 The Flow Measurement Facility

The Flow Measurement Facility was constructed especially for the experimental investigations to be conducted during this program. It was located adjacent to the building housing the Acoustics Laboratory at the Lockheed-Georgia Company Aerospace Sciences Laboratory above the Marquard Corporation Sudden Expansion (SUE) Burner already installed at this location. The entire set-up is mounted on a massive platform constructed

from 6-inch by 6-inch steel box beams with 1-inch thick steel plates on top to form a flat, essentially vibration free surface on which a center lathe having a 6-foot length bed was mounted. Three different flow measurement devices were designed and used on this facility during the program: a crossed beam schlieren system, a laser Doppler velocimeter, and a pulsed ruby laser interferometer. The center lathe was used as the most convenient system to obtain the required accurate translations of the various measurement devices in the downstream and transverse directions relative to the jet flow produced from any of the five nozzles designed and built for this program.

The main air supply continuously delivers 20 pounds per second of clean, cold dry air at 300 psi. In addition, storage tanks retain 12,000 pounds of air at 300 psi for higher flow demands. This main air supply is initially controlled with a 4-inch automatic regulating pressure control valve, which is located within the acoustics laboratory. This main control valve to some extent isolates the flow tests from pressure demand fluctuations in other facilities. Either temperature or pressure is used as the control function. Downstream of this valve cold air is delivered to the Marquardt Corporation Sudden Expansion (SUE) Burner through a 2-inch automatic regulating control valve. This valve is the primary controller on pressure within the burner system. The burner operates best at relatively high pressure and if test requirements dictate low pressure and low flow, hot air is bled off at the burner exhaust stack through a 2-inch, manually controlled high temperature, gate valve. In order to control both pressure and temperature accurately for the flow measurement tests hot and cold air are mixed upstream of the plenum mounted above the lathe on the flow facility. The cold air valve is automatically regulated by plenum pressure and the hot air valve is controlled by plenum temperature. These self-seeking servo controls provide simultaneous regulation of test pressure and temperature.

Descriptions of the mounting frames, etc., for each of the flow measurement devices is included in the appropriate chapters of Volume VI.

III.6.2 Some Fundamental Problems of Flow Measurement in Supersonic Jets

The study of jet noise falls logically into three categories: namely, the establishment of theoretical relationships between far field noise and the properties of the jet flow, measurement of the flow properties so defined and finally confirmatory measurements of the radiated noise. Of these three topics the first and third have, over the years, commanded far more attention than the second. In view of the impossibility, at present, of predicting the required flow properties on purely theoretical grounds and the important link they provide between theory and experiment, this relative lack of attention appears at first sight somewhat surprising. However, more mature consideration suggests two major reasons. First and foremost there has, until recently, been an almost complete lack of techniques for turbulence measurement in other than unheated jet flows of modest Mach number, where the use of the hot-wire anemometer is appropriate. By contrast, jet flows of practical interest are always hot and

sometimes supersonic; that is, these jet flows are flow regimes in which the use of this instrument is either extremely difficult or completely inappropriate, respectively.

Secondly, even for these flows where turbulence data is available no very direct link exists between conveniently measured flow parameters and the theoretically developed "source functions". These "source functions" as currently formulated, involve the evaluation of volume integrals of correlation functions of complicated velocity derivatives in which full account of retarded time effects is vital. As such the experimenter is faced with a practically impossible task. The integrand components in themselves are difficult to measure with accuracy, while the integral required inevitably involves a large degree of cancellation among the constituent integrands.*

In spite of such an apparently pessimistic outlook, flow measurement does have an important role to play in both the study and alleviation of the jet noise problem. At the level of basic understanding and prediction it is flow measurement which provides the necessary link between theory and experiment. This "link" is the measurement of the trends of the flow field properties with variation of controllable parameters such as jet efflux velocity, stagnation temperature, nozzle geometry etc., without which any proper comparison of theory and experiment is impossible. In this respect it is salutary to remember that turbulence parameters for supersonic shock containing flows are still commonly estimated from measurements made on relatively low Mach number flows. Until measurements on the flows of practical interest are readily available the doubt must always exist regarding whether it is the theory, as such, which is basically incorrect, or whether it is the turbulence estimates used to evaluate the theoretical work which are in error.

A second and equally important role for flow measurement lies in the furthering of our understanding and the optimization of various types of noise suppression devices, used in conjunction with aircraft exhaust nozzles. It is only as we learn to associate certain types of flow modification with improved acoustic performance that systematic improvement and optimization of such devices will be achieved. In essence the major task in jet noise research is to find methods of efficiently generating thrust with low associated noise levels. This can be achieved only by suitable modification of the jet flow field; a problem in aerodynamics.

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*Omitted from this discussion are those "source location" techniques which involve the use of one probe in the flow field and one in the acoustic far field. These methods do, in principle, offer some degree of relief from the problems cited above.

This will be achieved in a systematic manner only if our knowledge of the fluid mechanics is at least commensurate with that of the acoustic far field.

A task of importance, therefore, in any modern well-balanced study of jet noise must be the development of sufficient flow measurement techniques that, as a minimum, the general trends of both the mean value and turbulence properties of the flows of interest can be defined. In the longer term, as more techniques become available, precise estimates of the level of noise produced by various small portions of the flow are to be anticipated. However, considerable work in flow measurement techniques, data processing and theoretical work to develop "source functions" in terms of more readily measurable parameters will be required before any such techniques become "commonplace".

III.6.3 Flow Measurement Techniques

In the establishment of the flow measurement techniques to be investigated and developed in the course of this program the following criteria were considered essential.

a) The techniques must be of the "remote sensing" variety so that the type of flow disturbances associated with the insertion of probes into supersonic flow fields are avoided completely. It was felt that this criterion was absolutely essential for unsteady (i.e., turbulent) flow measurement since, to the best of our knowledge, methods for interpreting fluctuations measured behind a probe-generated shock wave, in terms of fluctuations which have occurred had the probe not been present, are not readily available. It should also be noted that even for mean value measurements the interpretation is rarely completely straightforward. For example, a total head tube is sometimes employed, in conjunction with the Rayleigh pitot formula, for the determination of local flow Mach numbers. What is not always appreciated is that interpretation of results requires a knowledge of either the stagnation pressure ahead of the probe-generated shock or the static pressure behind it. Neither piece of information is available in a shock-containing jet flow with the exception of that region of the potential core upstream of the first shock waves. These considerations led inevitably, therefore, to the choice of remote sensing optical techniques as the most promising avenue of approach.

b) The choice of remote sensing optical techniques inevitably leads to the question of methods of localizing the information and this raises a second criterion to be satisfied. For mean value information in flows of simple geometries this poses no significant problem. Numerical transforms exist (for example the Abel transform method for flows of circular symmetry) for the translation of integrated measurements to local values. However, for unsteady flow measurements, or for mean flow measurements where complicated geometries exist other methods are necessary. These fall basically into two categories: namely, the viewing

techniques or the crossed beam correlation technique. These methods differ significantly in their basic principle and hence both have advantages and disadvantages for various applications which merit some discussion.

The viewing technique relies for its application on radiation scattered from a primary beam into the field of view of an off-axis detector. The presence of scattering centers in the flow is therefore essential, the local "viewed volume" being defined by the intersection of the primary beam and the field of view of the detector optics. Its primary advantage is that time-history information is available from a relatively local volume of the flow. The disadvantages are the necessity of seeding the flow with scattering centers and in many applications the difficulty of controlling both the concentration and size of these particles, particularly at the flow rates required for jet noise applications. These difficulties are however minimized in the viewing technique application chosen for this program, namely the laser Doppler velocimeter (L.D.V.) method. Here it is the velocity of the particles which are of principle concern, their concentration and size being of secondary concern, though still important.

By contrast in the crossed beam method no attempt is made to measure local information <u>per se</u>. Two independent photo-detectors are employed, each of which registers an integral of all flow fluctuations which occurred along its line of sight. Localization of information is deferred until the data analysis stage. Cross correlation techniques are employed to retrieve <u>the statistics</u> of those fluctuations which are common to both detectors and which therefore occurred at the position common to their respective lines of sight. The disadvantages of the crossed beam method are that no local mean value information is obtained, while, in addition, only local statistics, as opposed to local time-history information, is available. Nevertheless these disadvantages are more than outweighed by some significant advantages. First and foremost, no seeding of the flow is required and in principle measurements can be made of naturally present flow properties such as pressure, temperature, density, etc.. In fact, measurements can be made of any flow property, variations of which can be made to modulate the power of a transmitted beam of radiation. Furthermore, and of particular relevance to measurements in high level acoustic environments, crossed beam systems can operate effectively with relatively poor signal to noise ratios as long as the noise component is not correlated between the two detection systems. Finally, many crossed beam arrangements are relatively rugged and inexpensive, not requiring the fine adjustment and high tolerance components required, for example, of interferometers.

c) After remote sensing optical techniques had been chosen and those methods had been defined which are available for retrieving local information from these devices it was finally necessary to choose the <u>flow properties to be measured</u> in this program of research. Clearly a balance had to be struck between the relative expense and feasibility of the

measurements and their relevance to jet noise research. In this respect it should be pointed out at the outset that Lighthill's acoustic analogy requires principally for its evaluation only turbulent velocity statistics, other mean flow quantities being eliminated in the analogy. However, more recent theories of jet noise, notably that due to Lilley reported herein, do take note of acoustic-flow interactions which appear to depend both on the mean velocity and mean temperature gradients. Since effects of the type predicted by Lilley are apparent in existing acoustic data, a requirement for measurement of both mean velocity and mean temperature gradients was taken into account in the choice of techniques to be developed in this program.

Undoubtedly, within the bounds of current jet noise theories, a principle need for flow measurement exists in the determination of the velocity fields, both the mean value and turbulent components thereof. Thus within the specification of remote sensing systems further work on the development of laser Doppler velocimeter techniques appeared essential and was undertaken. The ideal L.D.V. system for jet noise work is, of course, one in which the velocity time-history in at least two points of the flow can be monitored simultaneously. However, at the outset of this work the status of existing L.D.V. systems fell far short of this requirement. Two major problems required attention at the outset. These were the extension of maximum velocity capability over the majority of existing systems by something approaching one order of magnitude and a problem particular to jet flows, namely the large fluctuations of scatterer concentration which occur downstream of the nozzle as the primary jet flow mixes with the ambient air. The approaches adopted to overcome these problems and the status of the current L.D.V. are reported in Section III.6.5, following.

The choice of the remaining two systems was determined essentially on the following two requirements. First it was felt that a method should be available for determination of mean temperature profiles in view of their relevance in determining refraction of sound by the jet shear layers. Secondly a method was required for determination of the kinematic turbulent flow properties such as convection speeds, eddy scales, frequencies and eddy decay rates, all of which are of relevance to the evaluation of jet noise theories.

In principle there are two distinctly different methods via which these objectives may be achieved. The first involves the use of spectroscopic methods in which radiation is absorbed (or emitted) by a flow constituent to an extent determined by the thermodynamic state of that constituent. While such methods are experimentally straightforward and powerful in principle there are practical complications in applying them to hot jet flows containing combustion products. First the only major constituent of air which absorbs adequately is the oxygen content if radiation is chosen in the Schumann Runge band system, circa 1850 Å. Unfortunately, the absorption process is strongly wavelength dependent, thus requiring the use of fine resolution monochromators, which in turn requires

powerful light sources, not available for this spectral region. Finally, commonly present air contaminants, notably water vapor, are also powerful absorbers of this radiation, leading to interpretational difficulties as they are entrained into the primary jet flow. The only other possibility of absorption by naturally present air constituents is that of infra-red radiation by carbon dioxide. However, while such a system might be tenable for pure air, the presence of excess carbon dioxide due to combustion products in the primary jet again destroys any hope of unique interpretation. Thus spectroscopic techniques were reluctantly discarded at the outset of this program.

The remaining method is that of employing the variation of refractive index with air density. This offers a viable technique in three distinct ways. First, the flow density itself can be determined by using interferometeric techniques. Secondly, refractive index gradients or density gradients can be determined from measurement of the associated deflection of an optical beam: that is, by utilizing schlieren methods. Finally the second space derivatives of these quantities could be determined by using shadowgraph techniques.

In the present work attention has been restricted to the use of an interferometer for the measurement of mean density and hence mean temperature profiles and to the use of schlieren as the basic detection method for a crossed beam technique. The latter has been utilized principally as a method of determining the kinematic properties of the turbulent flow field.

To summarize, therefore, three flow measurement techniques have been considered and developed during the course of this program:

1) a laser Doppler velocimeter system developed initially for the measurement of mean velocity profiles in supersonic flows, but with the associated objective of extending the technique to the measurement of local velocity time-history data in these flows;

2) an interferometer system designed for the measurement of mean density profiles, from which mean temperature profiles can be inferred for the majority of situations of interest;

3) a crossed beam schlieren system designed principally for the determination of the kinematic turbulence properties of supersonic flows.

In the next three sections III.6.4-6, status reports on Phase I progress in the development of those three systems are given.

III.6.4 Status Report: The Crossed Beam Schlieren System

The crossed beam schlieren system has been both the least expensive and experimentally simplest optical flow measuring device of the three developed in this program. In spite (or, may we venture to suggest, because) of this it has been by far the most effective with regard to

measurement of turbulent flow properties. This remark however should not be interpreted as advocacy for neglect of the other techniques. The L.D.V., in particular, has considerable potential both in respect of what it measures and in unambiguous interpretation of results. Nevertheless for the measurement of kinematic flow properties, in particular, the crossed beam system has been very effective.

The details of construction, the test-program undertaken and the results obtained from the crossed beam system are presented in detail in Volume VI of this report. The system comprises, essentially, two low power lasers which pass narrow (0.8 mm diameter) beams of radiation across the jet flow field in two mutually perpendicular directions in a plane parallel to the nozzle exit plane. Each beam is arranged to be half cut off by a knife edge, that portion of the light passing the knife edge falling on a suitable photo-detector. Subsequent angular deviations of the beams produced by fluctuating density gradients in the flow field cause more or less light to pass the knife edges and are recorded as fluctuating electrical outputs for the photo-detectors. Each detector alone, of course, records only an integral of all fluctuations which have occurred along the entire length of the laser which it receives. However, cross correlation of the output of the two detectors eliminates much of this unrequired information, yielding local information about properties of the flow at the beam intersection point instead. The crossed beam system can be employed for measurement of the following flow properties: the intensities of the fluctuations, their frequency spectra and scales, the speeds with which they are convected and the rates of decay of the eddy field, or eddy lifetimes as they are often called. All of these properties were measured in the current program over a range of Mach numbers from 0.5 to 1.4, in both cold and heated jets. The results obtained indicate that the convection speed of the density field is close to 0.7 times the nozzle efflux velocity, independent of either jet operating conditions or radial location of the measurement. This agrees with previous observations of both Wilson (paper in Journal of Fluid Mechanics) and Harper-Bourne (ISVR Report) in subsonic unheated flows. It also agrees with pressure measurements, in both the jet potential core and entrainment region, made by Lau (to be reported in the Journal of Sound and Vibration), on the basis of which a reasonably simple model of the large eddy structure of jets was formulated. Further evidence for this similarity is to be found in the measured Strouhal number (based on jet diameter and convection speed) of the density fluctuations. This was again found to be independent of jet operating conditions and to have a value of order 0.75. This suggests a "wavelength" of the disturbances of order 1.3 nozzle diameters, which is close to the 1.25 nozzle diameters found by Lau to be the average spacing between successive vortices.

Further evidence for Lau's model was obtained from these results in terms of a large peak in the level of the density gradient fluctuation levels observed close to the interface between the shear layer and potential core, for the unheated jet cases. These are thought to be due to the

vortices inducing relatively warm air from the shear layer to flow into the relatively cold, dense potential core. Certainly this peak is observed to disappear completely when the jet is heated sufficiently to bring the air in the potential core up to the temperature of the ambient air. The main significance of these results is, therefore, that they suggest strongly that the relatively simple jet structure documented by Lau is not just a low speed phenomena but persists well into the supersonic speed range. Furthermore, it appears to be a major contributor to the near field pressure, although its ultimate role in the production of the acoustic far field is less certain.

The test program carried out here was designed specifically to examine the kinematic flow properties over a significant range of Mach number, both with and without jet heating. Future work requires a more systematic investigation of those parameters which control the amplitude of the observed fluctuations, although, as mentioned above and discussed in more detail in Volume VI, some useful information has already been obtained. This work will require initially operation of the available jet nozzles over a significant Mach number range with just sufficient heating to eliminate mean temperature gradients. It would then be extended to investigate systematically additional fluctuations created by turbulent mixing with temperature gradients present.

The work also needs extension to flows containing shock waves to examine the role of these, both in possible modification of the shear layer properties and in producing broad band shock-associated noise. Considerable experience in this type of measurement is already available, for unheated flows, at the University of Southampton, so that this extension should be relatively straightforward.

Finally, and the most important long term role envisaged for the crossed beam system, is the extension of the current work to examine the types of flow modification created by noise suppression nozzles. As stated previously, it is only with a fuller understanding of what constitutes acoustically advantageous flow modifications that work on jet noise suppression can proceed on a systematic basis. This constitutes an important role for flow measuring techniques and, based on experience with the current crossed beam system, there appears no reason why it should not begin to fulfill this role in the immediate future.

III.6.5 Status Report: The Laser Doppler Velocimeter

The intended use for the laser Doppler velocimeter (LDV) that was designed, constructed, and tested during this program was the determination of the axial component of the mean velocity profiles of the supersonic jet flow at various positions along the jet axis. The LDV was designed and constructed with provisions for movement of the entire rigid optics assembly along the jet axis and transversely on the lathe bed in common with other measurement systems in this program.

The principle of the LDV system is presented in detail in Chapter IV of Volume VI. The optical system chosen for the LDV utilized a forward scatter mode from the very small measurement or "probe" volume formed by the intersection of two focussed laser beams. These two beams, from a 5 mw helium-neon laser, intersect at a narrow angle forming interference fringes in the ellipsoidal measurement volume. When entrained dust particles, either naturally occurring or "seeded" pass through the measurement volume interference fringes, each particle scatters the laser light whose intensity is amplitude modulated at an RF rate. Only the forward scattered light from the measurement volume is collected by the optics system and is detected by a photodetector. The signal output at the photodetector is a series of very short RF "bursts", one for each particle passing through the measurement volume. The velocity of the particle, assumed to be imbedded in the air mass and following it exactly, is determined by measuring the frequency of the RF burst oscillations. This is made difficult, of course, because there are at most no more than 10 or 11 cycles of this frequency in the burst. The spacing of the interference fringes in the measurement volume and the velocity of the particle moving through it determine the frequency of the RF signal in the burst (30 Kc/(ft/s)). The fundamental problem of the LDV, as found in this application, is the method by which the frequency of this burst is determined.

Two approaches were considered and both were implemented. The first method was the use of a standard spectrum analyzer to determine the frequency components of the RF bursts. The center frequency of the Fourier components of the signal pulse corresponded to the frequency, and consequently, to the velocity in question. Two major problems were anticipated in the use of this method: the RF noise level of the photodetector masking the signal, and the expectation of a broadening of the signal spectrum and consequent lowering of the spectrum peak when making measurements in the turbulent shear zones at the jet flow. In practice, the signal to noise ratio for optimum seeding of the flow was not a problem; however, the sensible aspect of the spectrum in turbulent flows was not dependent upon seeding rates but was an inverse function of turbulence. Excellent results were obtained from the potential core region but errors were large in the turbulent mixing zones. Confirmation of the anticipated broadening and loss of spectrum center definition was shown to be a limitation of the use of the spectrum analyzer to determine signal frequency.

Some concern was also felt as to whether the interference fringes in the measurement volume would be stable in jet flows at high temperatures. This concern arose because of the long optical arm in the two beams transversing the hot gas might be refracted due to along-axis density variations, thus destroying the continuity of the very small measurement volume fringes. No difficulty in this respect was ever encountered.

When the utility limitations of the spectrum analyzer were clearly apparent, the adaptation of what was called the single particle detector

(SPD) was implemented. This second measurement method was a very different approach in that it processed the RF burst signal so as to measure the frequency of the oscillations directly. The basic circuit utilized signal processing to standardize the signal amplitude, converting it into a form amenable to direct digital counting of each cycle of the burst frequency. This was accomplished by a circuit design that afforded usable clock rates of 150 mc, although lower rates were used. This SPD circuit had been designed during an earlier independent development program at Lockheed-Georgia. As the circuit was implemented for this program, the output was in the form of a binary coded decimal (BCD) number that represented the number of counts that the high speed counter made, at its clock rate, during the course of time in which 5 cycles of the RF burst signal were received. Various digital and analog filters were used in the circuit to ensure that the output represented a good particle signal and was not the result of noise. Of particular concern were the signals from particles that did not pass through the center region of the measurement volume. After a considerable "teething" period the most serious problems of the circuit design were overcome and the system was functional.

A Lockheed Electronics Company mini-computer (MAC-16) was programmed to accept the BCD signals from the SPD. All computations, including signal averaging of specific numbers of particle velocities, were performed by the MAC-16 and this data was printed out on a teletype terminal. Since mean velocities were desired, the computer received and stored up to 420 particles before calculating a mean.

The system performed quite satisfactorily at all velocities and temperatures for the flow conditions chosen during this program. Errors of mean velocity calculation were small when measuring flows in the potential core. The individual particle velocities varied widely in the turbulent mixing zones, however, and this identified the primary problem of the system. Although the velocities were clearly real and the SPD was functioning as designed, it was clear that the assumption that each seeding particle was imbedded in the air mass and followed it exactly was not correct. Measurements made of the particle velocity showed that the particle continued to accelerate beyond the nozzle, and hence lagged behind the air mass. Calculations showed that the problem was centered in the choice of seeding particulate, a glassy material of micro-spheres commonly called "fly ash", which is an effluent from coal burning power plants. The seeding material had been chosen for its scattering capabilities, its mechanical and thermal stability, and served quite well. It was now clear that its characteristics were not optimum for accelerated flows such as the turbulent regions.

The two methods investigated to measure mean flow velocities, the spectrum analysis of the RF signal burst, and the SPD digital detection and computer calculation of individual and mean particle velocity, both performed satisfactorily. The SPD was developed in this application sufficiently to make clear the course that future development should take.

No problem was encountered that could not be solved or eliminated in the future. The primary problem, as it was shown, lay in the failure of the seeding particulate, due to size and variations of mass, to follow the air flow. Future development can rectify this by the utilization of smaller (i.e. 0.3 micron) particles having more uniform size and retaining the mechanical and thermal stability, such as magnesium oxide. This will, in turn, require more laser power levels at shorter wave lengths. Only minor revision to the present optical system will be required. There was little opportunity to explore the enormous potential of the computer to process the data received and stored. Real-time investigation of turbulence phenomena, at optimum seeding rates, is a fascinating future development to come from the SPD.

III.6.6 Status Report: The Pulsed Laser Interferometer

The basic purpose of the interferometer which has been designed, constructed and tested in this program is to provide information on the time-averaged density and hence temperature profiles which exist in hot supersonic jet flows. The basic principle, discussed in detail in Chapter IV of Volume VI, is relatively straightforward. It involves the comparison of the optical path experienced by sections of an entire radiation beam which have traversed various chordal sections of the jet flow with that portion of the same beam which passes only through the ambient air surrounding the flow. As is usual in interferometric work, this comparison is achieved by allowing this beam of radiation to interfere with a second independent plane reference beam. In the simplest conceivable situation, therefore, uniform illumination would be observed outside the flow field with interference fringes occurring as the differing density across the flow has created differences in optical path length.

Though simple in principle, there are several problems which must be faced in applying such a technique in practice to jet flows. First, and most basic, is that the jet density field is not steady but varying in time. The result of long term exposure of a photographic plate to record the fringes would therefore be a completely blurred image as the fringe positions move in sympathy with the changing density field. It was deemed, however, that this problem could be solved by using a pulsed laser so that the density field would be sensibly constant during the exposure period of order 10^{-8} second. Several such realizations would then be averaged to obtain the required mean value information.

The second problem involves the very critical tolerances required in the positioning of components in any optical interference system. It is seldom practical to build and maintain a system to such tolerances. Rather, good mechanical tolerances are provided with final adjustment being made by visual observation of interference patterns under known conditions. This technique is not practicable in the present system for a number of reasons. First, the use of a pulsed laser would make such adjustment extremely tedious, while, with a facility to be utilized

outside with the attendant high noise levels, it appeared unlikely that such adjustment could be maintained. It was decided to be better, therefore, not to attempt such adjustment on the flow facility itself but to record the phase information of the flow beam, together with any angular maladjustment errors of optical components, on holographic film. In the subsequent hologram reproduction procedure these maladjustments can be compensated under controlled laboratory conditions, the only assumption involved being that components in the optical system have remained optically flat. However, the main point is that critical angular adjustment on the flow facility itself is entirely avoided.

Such a system was constructed and tested over a representative range of jet flow conditions as described in Volume VI of this report.

The reproduction method chosen was to adjust the angular position of the hologram until a series of equally spaced parallel fringes were observed in the region outside the jet flow. As demonstrated in Volume VI, changes of this spacing across the flow region can then be utilized to obtain the required density information. An initial assessment of the reproduced holograms was extremely encouraging. The required equal spacing could be produced in the ambient flow region, while changing of this spacing was clearly apparent in the region of the jet flow. Furthermore, the fringes in both regions were relatively parallel to the jet axis, indicating that, as anticipated, the axial temperature gradients were small compared to those in the radial or cross-flow direction.

However, subsequent analysis of these interferograms revealed some notable discrepancies with anticipated results. As shown in Volume VI, a reasonable estimate for the optical path difference which exists between that section of the beam which traverses ambient air and that which crosses the jet diameter is given by

$$n \lambda_1 \sim 21\left(\frac{\rho_J}{\rho_A} - 1\right)$$

where λ_1 is the wavelength of the radiation used to produce the hologram and ρ_J and ρ_A are the density in the jet potential core and ambient flow region, respectively. An estimate of the former can, of course, be obtained from a knowledge of the jet operating conditions. Comparison with results obtained, however, showed that the measured optical path differences were in the majority of cases considerably in excess of this estimate. It was argued that the reason for this discrepancy could be that the instantaneous optical paths were not monotonic functions of position. Thus, a fringe shift which was interpreted as an increase of optical path was in fact a decrease. To investigate this possibility the presentation of the hologram reproduction was altered to yield fringes in the ambient air which were perpendicular, as opposed to parallel, to the jet axis. Again a convincing set of straight parallel fringes were obtained for the ambient region, while deviations in the flow region indicating changes of optical path due to the jet were again clearly apparent. However, again, on analysis, the indicated changes of optical path were far in excess of the theoretical estimate for the majority of the 173 cases examined. More serious, perhaps, is an apparent lack of

correlation between the magnitude of the optical path differences measured and the jet conditions. In many cases the measured path differences are as large or larger when no density difference existed across the flow field as when a significant difference was present.

A number of possibilities exist which require systematic investigation to resolve this apparent anomaly. The first and most serious is that an optical component in the hologram production system has become distorted, as a result of either temperature or acoustic stress. However, this seems a little improbable as the changes of optical path length, indicated by the interferograms, does begin to occur, in general, where other results, such as the crossed beam schlieren measurements, indicate the flow field begins. A second possibility is that entrainment of water vapor into the flow creates larger refractive index gradients than would exist if only pure dry air were entrained as assumed in the theoretical estimates. A final possibility that exists is that of subjective errors involved in the use of the reproduction system.

Although there are indeed some sources of subjective errors implicit in the use of the reconstruction system, particularly concerning the system sensitivity around the null (or condition of zero angular difference between hologram reconstruction beam and reference beam), experiments with a method of double exposure holograms showed that these subjective errors were very small. The double exposure holograms were made with one exposure of the jet flow and the second exposure of ambient air, no flow conditions. This procedure eliminated the necessity of an elaborate second set of optics to produce the interference patterns, and produced a set of fixed interference fringes in the hologram. The procedure also effectively eliminated the non-resolvable differences between the two optical systems.

The large errors that were consistently shown to be present in the long series of interference fringe patterns from the flow holograms made with single exposures were just as consistently absent from the double exposure holograms, although the number of samples were not nearly as large. The conclusion drawn from this observation is that the likely source of the problem lies somewhere in the production system optics. The pulsed ruby laser beam is divergently expanded in a negative lens prior to the collimation lens. The assumption that the small errors of alignment and collimation in the production system could be compensated for, to interferometric standards, in the reproduction optics system was reasonable only if the divergence of the ruby laser beam were held uniform over the diameter of the beam. The very high power density levels existing in the negative lens might well have induced small local distortions of the lens that made the divergence of the beam non-uniform. Such non-linearities could never be corrected by the reconstruction optics, but were a constant factor in the double exposure hologram system, and so had no apparent effect.

The very encouraging success of the double exposure holographic system demonstrated that vibration and distortion of the production optics under

acoustic stresses were not serious because they were not observed. A conclusion, therefore, of a qualified success for the pulsed laser interferometer may be drawn with reasonable confidence. This is that the double exposure hologram system, described in detail in Chapter V, Volume VI, together with the well developed interpretation methods for the interference fringe patterns, also described in Chapter V, Volume VI, will provide solutions to the problems encountered with the Holographic Interferometer. A systematic development of the double exposure system appears to be justified, and a very worthwhile next step.

CHAPTER IV

CONCLUSION

It is clear from the individual summary reports in Chapter III that, in general, it has been possible to successfully complete all the specific technical tasks comprising the Phase I Technical Plan (see Section III.2). The cases in which results achieved exceeded expectations considerably outnumber those in which disappointments were encountered. Somewhat surprisingly, no insurmountable difficulties arose.

Because the results obtained so closely matched up to the expectations, any specific conclusions from the work that could be usefully cited here have all been given previously in this volume, both in a generally implicit fashion in connection with the description of the objectives, scope of work and technical plan and in a detailed explicit fashion in the individual summary reports.

One overall conclusion only is necessary, or warranted. The general success of the Phase I program has fully validated both the approach adopted to the problem and the methods, both technical and organizational, used to implement it. For the same reason, the detailed results obtained in Phase I must largely dictate the formulation of the program for continuing future work (Phases II - IV), which is fully described in Volume II of this series of reports.